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Summary

Experimentally determined values of true secondary electron emission and relative values of reflected primary electron yield for a range of primary electron beam energies and beam impingement angles are presented for a series of novel textured carbon surfaces on copper substrates. (All copper surfaces used in this study were oxygen-free, high-conductivity grade.) In addition, a detailed description of the method of preparation of the surfaces is included. The purpose of this investigation was to provide information necessary to develop high-efficiency multistage depressed collectors (MDC's) for microwave amplifier traveling-wave tubes (TWT's) for communications and aircraft applications. To attain the highest TWT signal quality and overall efficiency, the MDC electrode surfaces must have low secondary electron emission characteristics. While copper is the material most commonly used for MDC electrodes, it exhibits relatively high levels of secondary electron emission unless its surface is treated for emission control. The textured carbon surface on copper substrate described in this report is a particularly promising candidate for the MDC electrode application. Samples of textured carbon surfaces on copper substrates typical of three different levels of treatment were prepared and tested for this study. The materials were tested at primary electron beam energies of 200 to 2000 eV and at direct (0°) to near-grazing (85°) beam impingement angles. True secondary electron emission and relative reflected primary electron yield characteristics of the textured surfaces were compared with each other and with those of untreated copper. All the textured carbon surfaces on copper substrates tested exhibited sharply lower secondary electron emission characteristics than those of an untreated copper surface. Of the three textured surfaces tested, one clearly yielded the lowest emission characteristics.

Introduction

The achievement of high collector efficiency is a requirement for the development of high-efficiency microwave amplifier traveling-wave tubes (TWT's) for space communications and aircraft applications. The invention, development, and use of the multistage depressed collector (MDC) for these tubes (ref. 1) has been a major contribution in this effort. Among the significant factors in maximizing MDC efficiency is the use of electrode materials having low secondary electron emission characteristics. Specifically to recover the maximum kinetic energy from the spent electron beam after it has passed through the radiofrequency interaction section of the TWT and entered the MDC, the electrodes must have low secondary electron emission characteristics (ref. 2) so that the electrons are not excessively reflected or reemitted from the surfaces. While copper is the material most commonly used for MDC electrodes, it exhibits relatively high secondary electron emission if its surface is not treated for emission control.

A number of methods have been used which modestly reduce the secondary electron emission properties of the copper MDC electrode surfaces including coating the surfaces with compounds known to have lower secondary electron emission characteristics than copper itself and also roughening the surface. Some forms of graphite or carbon have also been recognized as being suitable candidates for MDC electrodes. Experimental investigations conducted at the NASA Lewis Research Center demonstrated that the low secondary electron emission properties of pyrolytic graphite and high-purity isotropic graphite can be further reduced to the lowest levels ever observed by appropriately ion-texturing their surfaces (refs. 3 to 7).

The textured carbon surface on a copper substrate described in this investigation is a very promising candidate for MDC electrodes. (All copper surfaces used in this study were oxygen-free, high-conductivity grade.) This surface exhibits extremely low secondary electron emission characteristics which compare very closely with those of the ion-textured pyrolytic graphite and high-purity isotropic graphite examined in the earlier studies (refs. 6 and 7). The use of this surface may be particularly attractive to the several TWT manufacturers currently using copper electrodes, since it may increase the efficiency of the MDC without significantly changing its basic design or fabrication procedures. In addition, the continued use of copper as the basic MDC electrode material may be desirable for those TWT manufactures reluctant or unwilling to use graphite electrodes until the fabrication and brazing technology for including graphite electrodes in MDC assemblies is further developed and reliability is assured by long-term testing. Further, since the textured carbon layer on the copper substrate is extremely thin, outgassing procedures for high-vacuum, high-voltage applications can be relatively simple and require only brief processing periods, as opposed to those that may be required for graphite or carbon electrodes, which are porous and necessarily much thicker because of structural requirements.

To properly assess the effectiveness of the proposed MDC electrode materials, it is necessary to have a good knowledge of their secondary electron emission characteristics over a representative range of electron-beam energy levels and over a wide range of electron-beam impingement angles. This report is intended to contribute to that knowledge of the textured carbon surface on a copper substrate.

Background Information

High-efficiency microwave amplifier TWT's use MDC's. The magnetic field that confines the electron beam in the radiofrequency interaction section of the TWT is removed at the MDC entry port. The beam diverges from this point, and the electrons are slowed by a retarding electrical field and are collected selectively by their energies, with relatively small losses. The MDC efficiency is directly influenced by the ability of the electrodes to capture and retain the impinging electrons. To attain the highest efficiency, the electrodes must have a low secondary electron emission ratio; that is, the ratio of remitted electrons to impinging electrons must be low. Secondary electron emission, as an MDC loss mechanism, is discussed in references 3 and 6.

Copper and Treated Copper Surfaces

Copper is the metal most commonly selected for MDC electrodes because of its high thermal and electrical conductivity as well as its ease of fabrication. The relatively high secondary electron emission characteristics of untreated copper, however, make it a poor candidate for use as electrodes in high-efficiency MDC's. Treatments to provide copper surfaces with reduced secondary electron emission properties include the topical application of materials having lower emission levels than those of untreated copper.

Probably the most common example of that approach is the sputtered application of a thin coating of titanium carbide to the copper substrate, a technique which has been shown (ref. 3) to moderately reduce the secondary electron emission characteristics. An even more effective method to reduce the secondary electron emission characteristics of copper is to modify its surface by ion-texturing (ref. 7). When the copper surface is subjected to argon ion bombardment in a low-pressure environment under the proper conditions, a highly textured surface results. This surface exhibits significantly lower secondary electron emission properties than those of untreated copper. It should be noted that a higher melting-point material, such as tantalum, must be sputtered simultaneously on the copper surface during ion bombardment to produce the desired textured surface (as described in ref. 7). While the copper surface treatment and modification methods described here are effective in producing secondary electron emission properties lower than those of untreated copper, the attainment of even lower levels is desirable for electrodes in high-efficiency MDC's.

Untreated and Ion-Textured Graphite Surfaces

The known low secondary electron emission characteristics of carbon focus attention on this material as being potentially useful for MDC electrodes. In its simplest form, soot, it is an easily applied and consistently reproducible control surface having extremely low secondary electron emission characteristics to which the secondary emission properties of other materials may be conveniently compared. While soot is unsuitable for use in an actual MDC because of its poor adhesive properties, it is very useful as a control surface, and it was employed in this investigation. The low secondary electron emission characteristics of pyrolytic graphite and high-purity isotropic graphite may be reduced even further by ion-texturing the surfaces (refs. 3 to 7). All the graphite surfaces studied in these references, either untreated or ion-textured, displayed sharply lower secondary electron emission properties than those of untreated copper over the range of conditions examined. The ion-textured graphite surfaces investigated in the studies reported in references 6 and 7 displayed the lowest secondary electron emission properties observed to date and clearly provide the potential to improve MDC efficiency and therefore the overall TWT efficiency when used as MDC electrodes.

Textured Carbon Surface on Copper Substrate

The surface that is the subject of this report is a thin, adherent, highly textured carbon layer on a supporting copper underlayer. The carbon surface is characterized by a dense random array of microscopic peaks, or spires, which are essentially perpendicular to the local copper substrate. The surface closely resembles the surfaces of the ion-textured graphites reported in references 6 and 7. As described in the Introduction of this report, the use of the textured carbon surface on a copper substrate as an MDC electrode material may be quite attractive to TWT manufacturers, since fabrication procedures for copper are well developed and also because vacuum processing procedures for this surface do not appear to be complicated or costly. The preparation of this surface and its experimentally determined secondary electron emission characteristics are the subject of the remainder of this report.

Apparatus and Procedure

Apparatus for Depositing Textured Carbon on Copper Substrate

A schematic of the apparatus used for producing the textured carbon surface on the copper substrate samples studied in this investigation is presented in figure 1. The vertically mounted cylindrical plasma chamber (o.d., approx. 38 cm (15 in); height, 24 cm (9.5 in)) is a 30-cm argon ion source which was modified from a previous use (ref. 8). The plasma chamber uses a hollow cathode which includes a porous

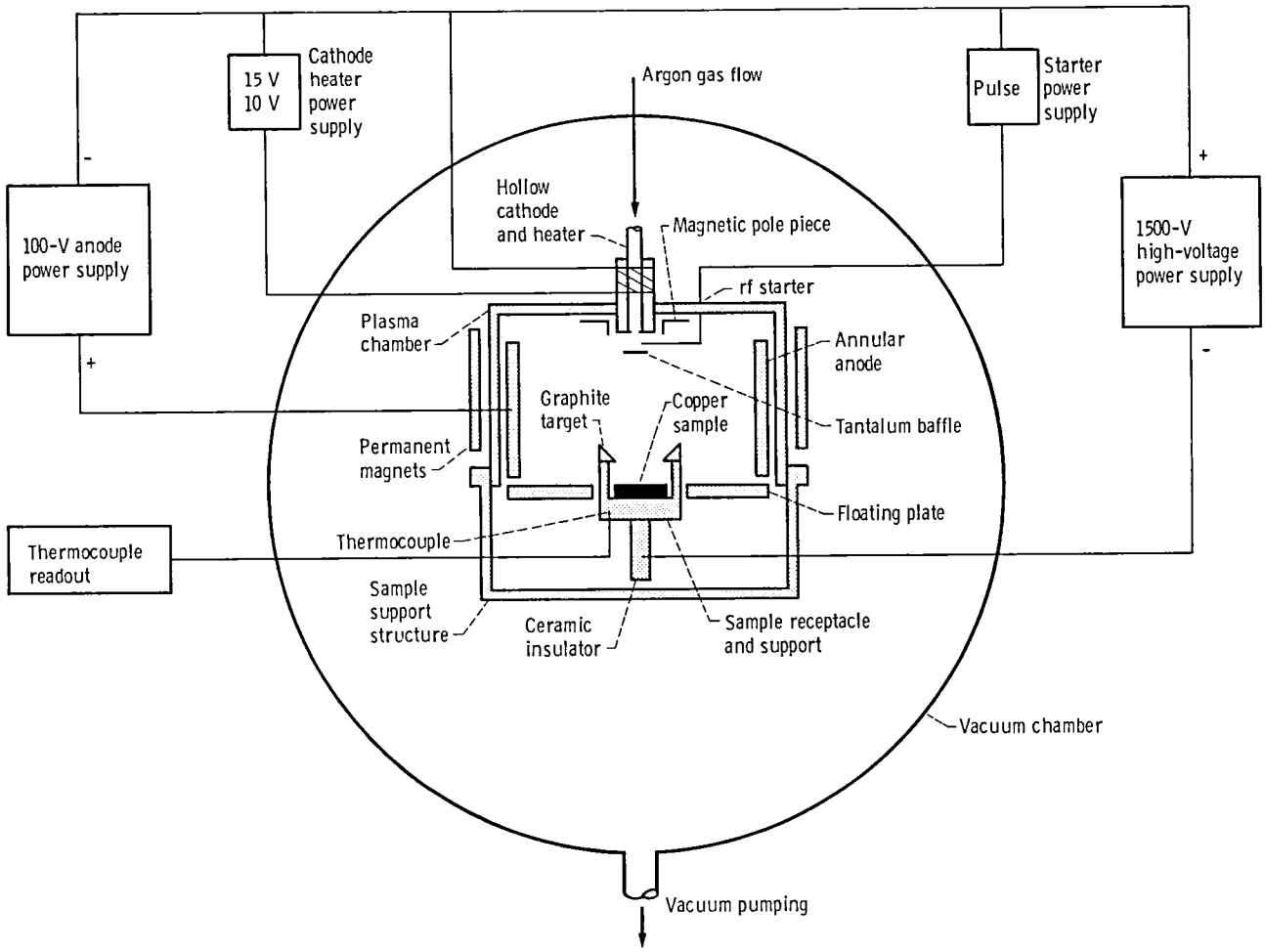


Figure 1.—Schematic of apparatus used for sputter-deposition of textured carbon on copper substrate.

tungsten cylindrical insert impregnated with barium oxide as a dispenser of the low-work-function material. Argon gas is passed through the hollow cathode and into the chamber through a 0.076-cm- (0.030-in-) diameter orifice. The plasma discharge is initiated by applying a brief 3-kV pulse to a probe located 0.2 cm (0.079 in) from the cathode tip. Details of the pulse starting procedure are included in reference 8. The copper substrate samples, on which the textured carbon surface was applied, were disks approximately 2.1 cm (0.828 in) in diameter and 0.15 cm (0.060 in) thick. The samples were positioned in a carbon receptable fitted with a graphite sputtering target (fig. 1), which is described in greater detail in the Sample Fixture and Substrate Preparation section. The sample support receptable is instrumented with thermocouples to monitor the sample temperature during the deposition process. An electrically floating solid plate surrounds the receptable and restricts plasma to the sample location.

The plasma chamber is operated inside a large vacuum chamber which is about 91.5 cm (3 ft) in diameter and about 61 cm (2 ft) long. The large chamber is equipped with pumps of such capacity that a pressure of about 1.33×10^{-4} Pa (1×10^{-6} torr) can be maintained with no argon gas flow and pressures from about 2.66×10^{-3} to 7.98×10^{-3} Pa (2×10^{-5} to 6×10^{-5} torr) can be maintained when argon gas is being introduced into the plasma chamber. For easy access to the equipment, the plasma chamber is attached to a removable door of the large vacuum chamber as shown in figure 2. The chamber door is fitted with appropriate vacuum feedthrough devices to accommodate both the instrumentation leads and gas lines (fig. 1).

Operating procedures.—After the copper substrate disk to be treated and the sample support receptacle are positioned, the vacuum chamber is closed, sealed, and pumped to about 1.33×10^{-4} Pa (1×10^{-6} torr). Argon is then ducted into the plasma chamber through the hollow cathode at a rate of about 70 to 80 standard cm^3/min, and the cathode heater power and anode power are applied. After the cathode reaches its operating temperature, an ion discharge is established by briefly activating the high-voltage pulser. Ion bombardment of the sample surface is started by activating the high-voltage power supply to establish a potential difference between the plasma and the sample. The sample surface current density is determined by dividing the high-voltage power supply current by the projected area of the carbon sample receptacle

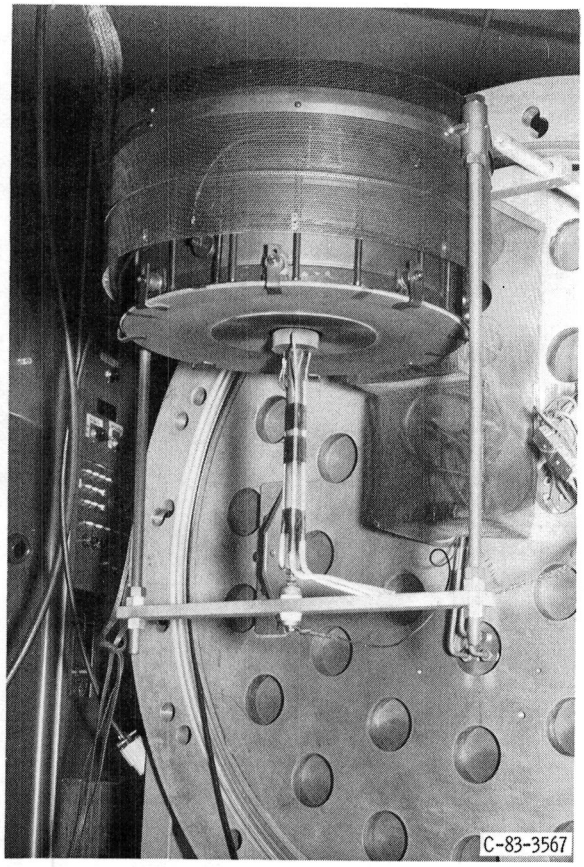


Figure 2.—Sputter-deposition apparatus showing sample support structure and receptacle in position.

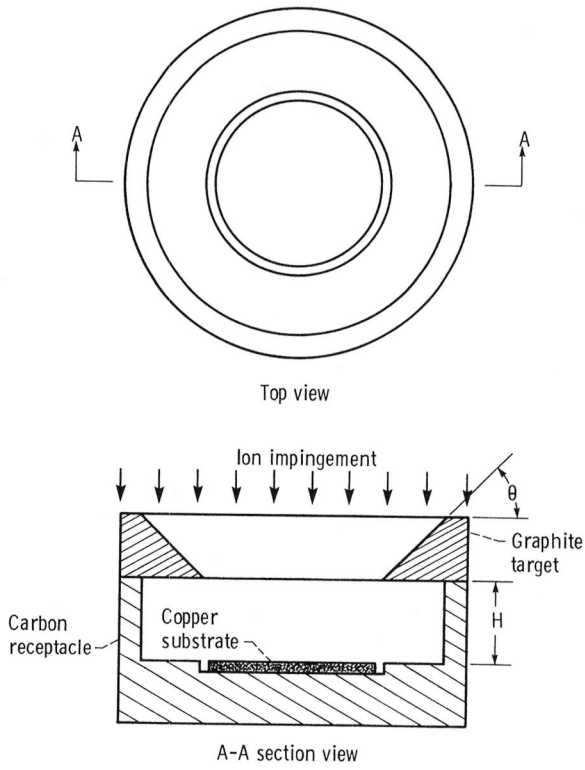


Figure 3.—Section schematic of copper sample disk support receptacle for sputter-deposition apparatus.

exposed to the plasma. After deposition of the carbon begins, the various operating parameters may be adjusted to provide the desired sample surface current density and to ensure operating stability. The argon flow rate is commonly reduced to between 40 and 60 standard cm^3/min, and the cathode heater power may also be reduced significantly. The length of time the deposition, or texturing, continues is at the option of the operator.

Sample fixture and substrate preparation.—The textured carbon surfaces on the copper substrate samples investigated in this study were produced by using the triode sputter-deposition process described in the Operating procedures section. In this process a high-purity graphite target and the copper substrate were held at common electrical potential and were simultaneously bombarded by an argon plasma in a low-pressure environment. Figures 3 and 4 show the sample fixture arrangement which produced the most uniform coverage and greatest carbon spire development. The carbon deposition results were most satisfactory when the target inside diameter and the diameter of the substrate area to be treated were nearly equal, when the angle of the target surface relative to the substrate θ was about 45° (± 10°), and when the spacing from the bottom edge of the target to the substrate H was about one-half the diameter of the substrate area to be treated (see fig. 3). While these target-substrate dimensional relationships are

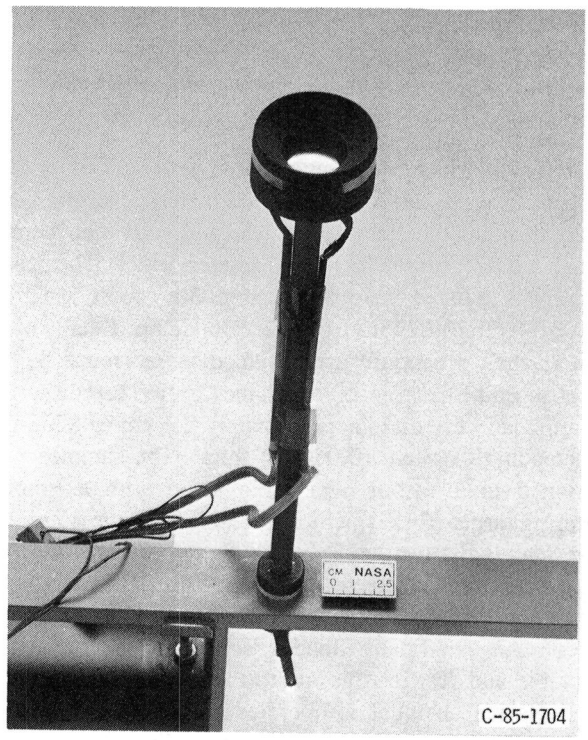


Figure 4.—Sample support receptacle and structure with copper sample disk in position before installation in sputter-deposition apparatus. Wires shown are leads for thermocouples located in receptacle.

not presented as rigorously determined requirements, significant variations from these very general guidelines resulted in generally unsatisfactory surface coverage and feature development. Many other sample fixture configurations and target-substrate electrical biasing combinations are possible, some of which may produce quite satisfactory results; however, a comprehensive survey of these other arrangements is beyond the scope of the present study.

Before the textured carbon was applied to the copper substrate sample disks, surface dirt was removed from the copper by gentle abrasion with extremely fine sanding cloth, and the copper was wiped with high-purity ethyl alcohol on clean, lint-free cloth or absorbent paper. No other preconditioning of the samples was performed or found to be necessary.

Secondary Electron Emission Evaluation

The facilities and procedures used to evaluate secondary electron emission characteristics of the sample surfaces are described in detail in reference 6. Briefly, the samples were attached to a micromanipulator-mounted support fixture and installed in an ultra-high-vacuum vessel equipped with a scanning Auger spectrometer cylindrical mirror analyzer (CMA), which has an integral electron gun, a residual gas analyzer, vacuum feedthrough fittings, and other associated equipment. A filament heater-reflector system and a thermocouple were incorporated into the sample-holding fixture for sample degassing and temperature monitoring. The vacuum chamber was evacuated to a pressure of 1.33×10^{-8} Pa (1×10^{-10} torr) or less for testing. During the pumpdown the entire vacuum chamber was heated to about 250 °C for 16 hr to degas the system. The sample was then heated by filament radiation and electron bombardment to about 500 °C for 3 to 4 hr to further degas the sample and to simulate the anticipated bakeout temperature to which an MDC assembly on a TWT would be subjected. Along with the secondary electron emission measurements, Auger spectroscopic examinations were conducted to determine the chemical composition of the sample surfaces, as discussed in the Experimental Results section.

One-half of each sample disk was coated with soot to provide a control surface. The affected areas of the textured carbon surfaces were sanded to return the surfaces as nearly as possible to their untreated condition before the soot coating was applied. During the evaluation of the sample surfaces for secondary electron emission characteristics, tests were routinely performed at two or more locations on each half of the disk surface. This procedure helped to ensure the validity of the data since the known very low secondary electron emission characteristics of soot provided a standard that would immediately indicate errors in procedure or instrument function should they occur.

The surfaces were evaluated for true secondary electron emission and reflected primary electron yield characteristics at 11 primary electron beam energy levels from 200 to 2000 eV for each of eight beam impingement angles from 0° (directly impinging) to 85° (near grazing). For each angle the electron gun was focused to produce a spot about 10 μm in diameter on the sample. Tests were repeated at identical conditions and yielded reproducible results (within limits of measurement) in every instance. Scanning-electron-microscope examinations after lengthy periods of testing revealed no observable surface damage from electron beam impingement on any of the samples.

True secondary electron emission.—In true secondary electron emission, electrons undergo inelastic collisions at or near a solid surface that is undergoing electron bombardment and are emitted from that surface with energies of the order of a few tens of electron volts. A sample-biasing method that is described in detail in reference 6 was employed to determine the true secondary electron emissions characteristics of the surfaces investigated in this study. With the electron beam focused on the sample surface with a given beam energy, the measured sample-to-ground current was taken to be the total beam current I_b minus the secondarily emitted current I_s. When an appropriate positive bias voltage (in this case, 90 V) was applied to the sample, the true secondary electrons were retained by the sample, and the resulting sample-to-ground current was taken to be the total beam current. The true secondary electron emission ratio δ, the ratio of true secondarily emitted electrons to primary electrons, was calculated by the expression

$$\delta = \frac{I_b - (I_b - I_s)}{I_b}$$

where

$I_b - I_s$ beam current minus secondarily emitted current (0.14 to 2.5 μA in this study)

I_b beam current (0.29 to 3.3 μA in this study)

Reflected primary electron yield.—In reflected primary electron yield, electrons experience elastic collisions at a solid surface that is undergoing electron bombardment and are reflected from that surface with energies at or very near the primary electron beam energy. The method used in evaluating the reflected primary electron yield for the surfaces studied in this investigation was adapted from that used in reference 3. The Auger CMA was used to characterize the reflected primary yield at each primary electron beam energy investigated. The quantity used as a measure of the relative values of reflected primary yields from different surfaces at a given primary electron beam energy and impingement angle is the reflected primary electron yield index, π. This is the ratio of the amplitude of the elastic energy peak for a given surface and a given primary electron energy to the amplitude of the elastic energy peak for the control soot surface at the same beam impingement angle and a primary electron beam energy of 1000 eV:

$$\pi = \frac{D_{\text{sample}}}{D_{\text{control}}}$$

where

D_{sample} elastic curve amplitude for sample surface at a given primary electron beam energy

D_{control} elastic curve amplitude for soot control surface at 1000-eV primary electron beam energy

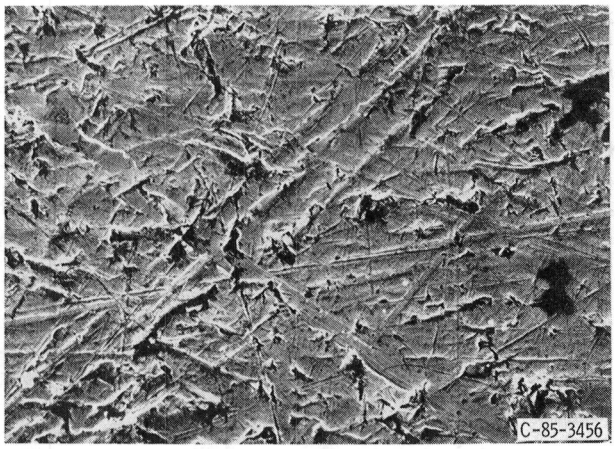
As stated earlier, soot was selected as the control surface (as it was in ref. 3) because of its known extremely low secondary electron emission characteristics and because its results can be readily reproduced. Although this method does not determine the absolute value of the reflected primary electron yield, it serves the important purpose of permitting comparison of this property for different surfaces.

Note that the reflected primary electron yield that was measured in this study was based only on those electrons that were accepted into the annular analyzer port of the Auger CMA. This is the most important direction of reflected primary yield from the standpoint of MDC efficiency since the reflected primary electrons can retrace the paths of the primary electrons and reenter the interaction region of the TWT.

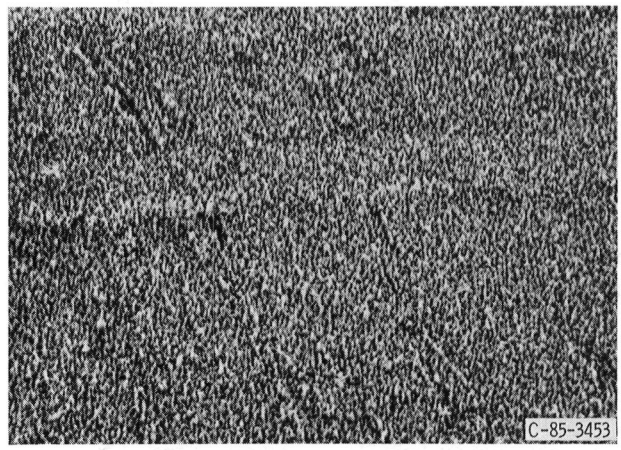
Experimental Results

Surfaces Investigated

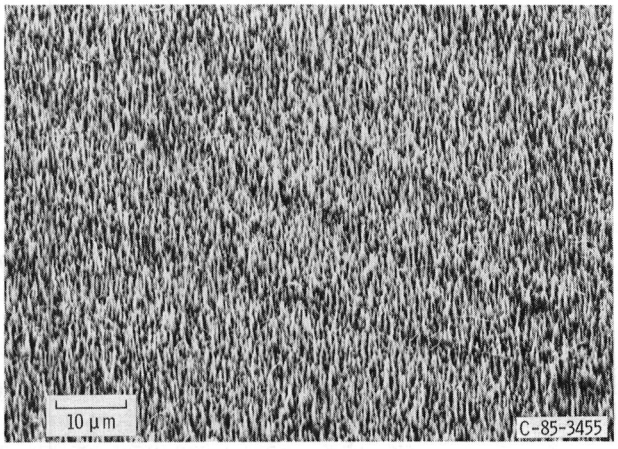
Scanning-electron-microscope photomicrographs of the four surfaces studied in the investigation are presented in figures 5(a) and (b). In figure 5(a) the surfaces are shown at medium magnification, while higher magnification views of the same



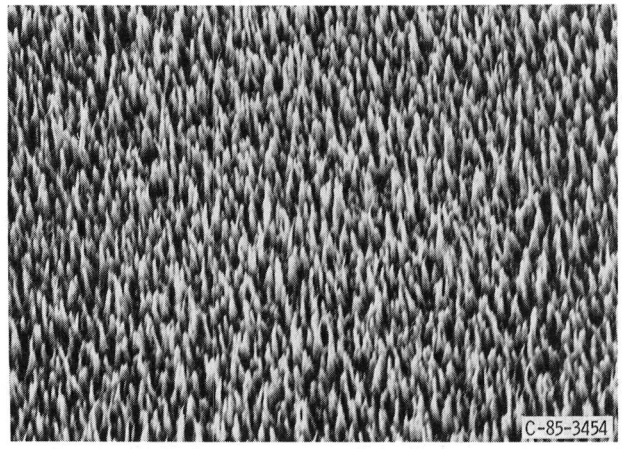
Untreated copper surface



Sample 1; textured carbon surface on copper substrate; texturing period, 1 hr; temperature, 455 °C.



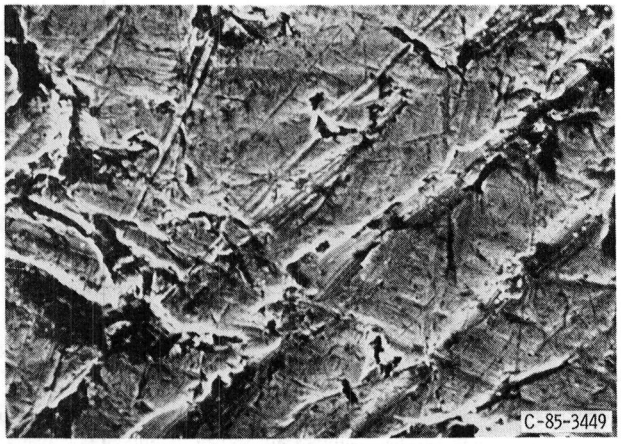
Sample 2; textured carbon surface on copper substrate; texturing period, 2 hr; temperature, 455 °C.



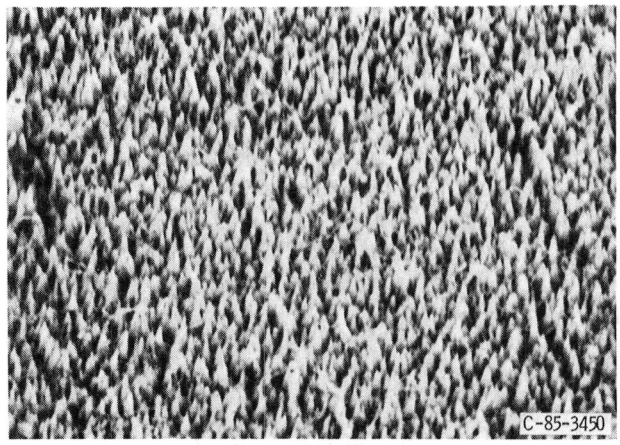
Sample 3; textured carbon surface on copper substrate; texturing period, 3 hr; temperature, 495 °C.

(a) Medium magnification; original photomicrographs taken at magnification of 1000.

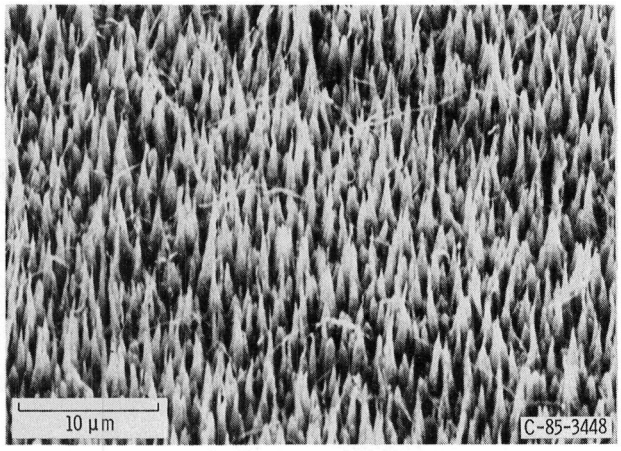
Figure 5.—Scanning-electron-microscope photomicrographs of untreated copper surface and textured carbon surfaces on copper substrates examined for secondary electron emission characteristics. Angle with surface, 30°. Common texturing parameters: accelerating potential, 1500 V dc; argon flow rate, 30 to 40 standard cm^3/min; surface current density, 5 mA/cm^2; vacuum chamber pressure, 2.66×10^{-3} to 5.32×10^{-3} Pa (2×10^{-5} to 4×10^{-5} torr). Temperatures noted are for sample receptacle at end of texturing period.



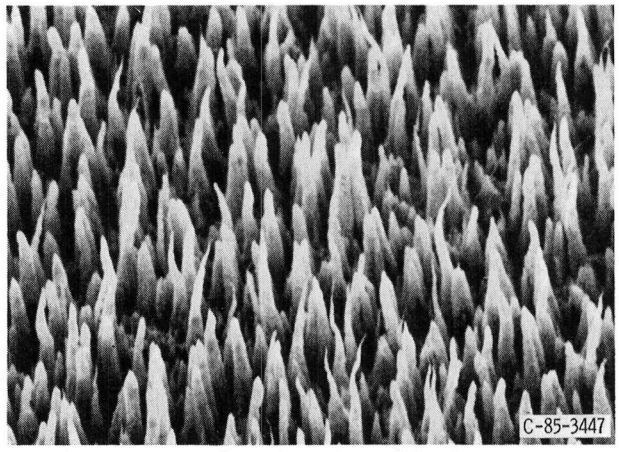
Untreated copper surface



Sample 1; textured carbon surface on copper substrate ; texturing period, 1 hr; temperature, 455 °C.



Sample 2; textured carbon surface on copper substrate ; texturing period, 2 hr; temperature, 455 °C.



Sample 3; textured carbon surface on copper substrate; texturing period, 3 hr; temperature, 495 °C.

(b) High magnification; original photomicrographs taken at magnification of 2850.

Figure 5.—Concluded.

surfaces are presented in figure 5(b). Included in both figures are photomicrographs of an untreated copper surface and three textured carbon surfaces on copper substrates identified as samples 1, 2, and 3. While all three surfaces were prepared by using the same basic procedure, samples 1, 2, and 3 were textured for different periods, 1, 2, and 3 hr, respectively. Based on the examination of a relatively large number of textured carbon surfaces on copper substrates, the surfaces studied are considered to be typical for the texturing procedures described in this report.

It must be noted that the texturing procedures used for the experimental surfaces examined in this investigation are not necessarily presented as those which produce optimum surface texture development or secondary electron emission suppression. Rather, the procedures and operating parameters described in this study are those which were found, after considerable experimentation, to produce effective results and which were convenient to use with the facilities available. Perhaps some modifications or the substitution of equivalent procedures might also result in equivalent results. It is beyond the scope of this study to include a comprehensive survey of this topic.

Textured surface characteristics.—The development of the textured carbon surface features as a function of the texturing period is apparent from a comparison of the photomicrographs of the sample surfaces. In the medium magnification photomicrographs of figure 5(a), the very small and relatively immature spires of sample 1 (textured for 1 hr) barely cover the copper surface, and the very shallow, scratchlike depressions of the substrate strongly influence the appearance of the surface. The spires on the surface of sample 2 (textured for 2 hr) are more developed than those of sample 1 and provide improved coverage of the copper substrate scratches and depressions. The even more mature spires of sample 3 (textured for 3 hr) completely cover and totally obscure the copper substrate surface features. A significant common

characteristic of all three textured surfaces is that the coverage is very uniform, indicating that the textured carbon application is apparently not adversely influenced by minute substrate surface irregularities.

An examination of the high-magnification photomicrographs of the textured sample surface in figure 5(b) reveals, in addition to the differences in substrate coverage, some significant changes in the feature formation as a function of texturing period. While the spires on the surface of sample 1 (textured for 1 hr) are fairly uniform in height and spacing, about 2 and 1 μm, respectively, the spires on the surface of sample 2 (textured for 2 hr) show a change in development and growth patterns. Many of the spires are joined together in groups of two or more. Further, the groups of joined spires indicate accelerated growth, since they are much larger and higher than those spires which remained as individuals. The groups of spires on the surface of sample 2 have average heights and spacings of about 4 and 2 μm, respectively. The individual spires are approximately sized and spaced the same as on sample 1. In addition, very fine tendrils, or threads, of carbon are attached to the tips of some of the spires of sample 2. The cause of formation of these tendrils is unknown. The surface of sample 3 (textured for 3 hr) displays additional spire groupings and further differential growth of the groupings relative to the individual spires. The large spire groups of sample 3 have average heights and spacings of about 6 to 12 μm and 3 to 6 μm, respectively. Many individual spires have not grown in height beyond the level observed on the surface of sample 1. The reasons for the spire grouping and differential spire growth patterns as well as the almost complete absence of carbon tendrils on the surface of sample 3 are open to speculation at this time.

Although not included in this report, photomicrographs were also taken of textured carbon surfaces on copper substrates which were textured with the same procedures as for samples 1, 2, and 3, but textured for periods of 1/2 and 4 hr. The sample which was textured for 1/2 hr displayed incomplete (about 60 percent) and nonuniform surface coverage, and the deposited carbon particles were of no particular shape. The surface was considered to be of no value for the purpose of this investigation and was not studied further. The surface textured for 4 hr, however, displayed spire formation and coverage essentially identical in appearance to those of sample 3. Because of the lack of significant differences between samples textured for 3 and 4 hr, data for the longer texturing period were considered to be of limited value for this report and were therefore omitted.

The difference in physical appearance between an untreated copper surface and a textured carbon surface on a copper substrate is demonstrated in figure 6. The naturally dark surface one would expect with a carbon layer on the copper surface is made still darker by the light-reflectance-suppressing effect of the spire structures on the textured carbon surfaces.

Surface thickness and substrate effects.—Figure 7 presents an electron-microscope photomicrograph of a section of a

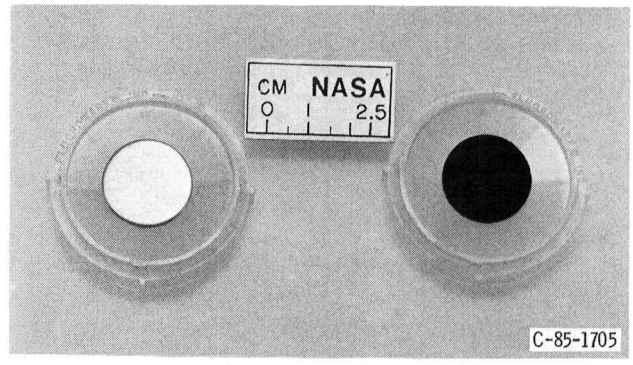


Figure 6.—Contrast in appearance of untreated copper (left) and textured carbon on copper surface. Samples are shown in storage containers.

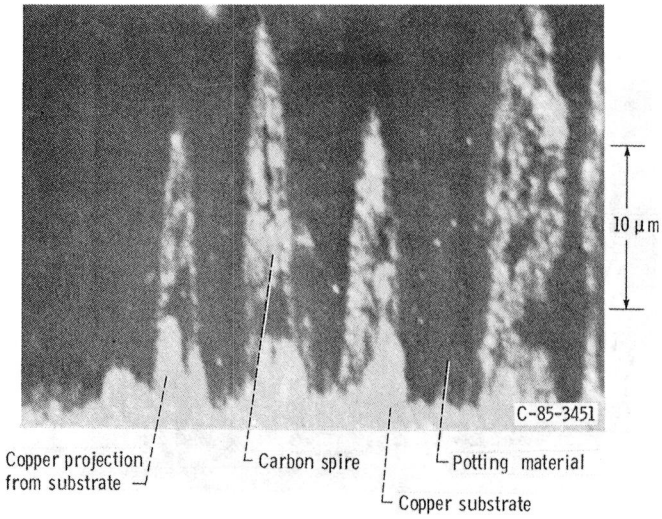


Figure 7.—Electron-microscope photomicrograph of section of textured carbon surface on copper substrate.

textured carbon surface on a copper substrate. This and other similar photomicrographs reveal that each carbon spire is formed on a very small projection from the copper substrate surface. The spaces between the copper projections on the fully textured surface are occupied by the carbon that forms the bases of the spires. The copper projections were not present on the untreated substrate but were apparently formed during the early stages of the texturing period. The very intimate and complex carbon-copper interface suggests that a very good thermal and mechanical bond exists at the interface.

After the nature of the carbon-copper interface was observed, an untreated copper substrate was subjected to a blasting treatment with very small silica particles to create small surface irregularities. This was done to determine whether small copper projections might accelerate the formation of the carbon spires, and thereby reduce the texturing period required to produce a satisfactory textured carbon surface. Limited experimentation indicated no reduction in the required texturing period or improvement of the textured carbon surface was accomplished by this substrate pretreatment procedure.

Textured carbon surface damage susceptibility.—The carbon spires on the surface of the textured samples may be damaged or destroyed by mechanical abrasion. Unless the abrasion is very vigorous or continued for an extended period, however, the depressions between the copper projections on the substrate will retain the carbon which has been deposited there and an essentially continuous and relatively smooth carbon surface will be maintained on the substrate. Limited testing has indicated the secondary electron emission suppression of such an abraded surface, while significantly inferior to those of an undamaged textured carbon surface, is nevertheless still much superior to that of an untreated copper surface. The secondary electron emission characteristics of the abraded surface are quite similar to those of a sooted surface on a smooth copper substrate (ref. 6).

Sample surface Auger spectrographic examinations.—Auger spectrographic examinations of each sample surface tested were performed both before and after the samples were baked out or degassed at 500 °C for several hours. The Auger spectra presented in figure 8 for sample 3 are typical of those for all the textured carbon surfaces on copper substrates included in this study. The dominant element present in both the pre- and postbakeout spectra is, of course, carbon, with indications of argon (the bombarding ion), oxygen, and a trace of copper. The postbakeout plot, produced with the same sensitivity parameters as the prebakeout plot, indicates significantly reduced amounts of argon and oxygen. Although the remaining argon would probably be essentially completely removed in an extended bakeout process, the small amount of oxygen still present is thought to be combined with copper in a copper oxide and would resist removal by the bakeout temperature used in this study.

Secondary Electron Emission Measurements

The experimental results presented in this report are not average or mean values for several "identical" test conditions but are specific values for one particular test series for each surface examined that are judged to be typical for that surface. A relatively large number of test series were performed during the investigation to form the basis of that judgement. Furthermore, specific test conditions were repeated routinely for each surface at different locations on the surface to assure the validity of the data record. Scanning-electron-microscope examinations were conducted for each surface to assure uniform conditions and to reduce the possibility of inadvertently selecting an atypical location for testing.

True secondary electron emission.—For each of the three textured carbon surfaces on copper substrates studied in this investigation, as well as the untreated copper surface included for comparison, the true secondary electron emission ratio generally increased with increasing electron-beam impingement angle at all points over the primary electron energy range examined. This is illustrated in figures 9(a), 10(a), 11(a), and 12(a), where the emission ratio is plotted as a function of primary electron energy for each of the electron-beam impingement angles examined. For the untreated copper surface (fig. 9(a)), the secondary electron emission characteristics of which were reported in reference 7, the tendency for the emission ratio to increase is attributed to the impinging electrons penetrating to decreasing distances below the surface as the beam impingement angle is increased. The electrons which are involved in the inelastic collisions then have shorter distances to travel to escape the surface and therefore do so in increasing numbers as the beam angle is increased.

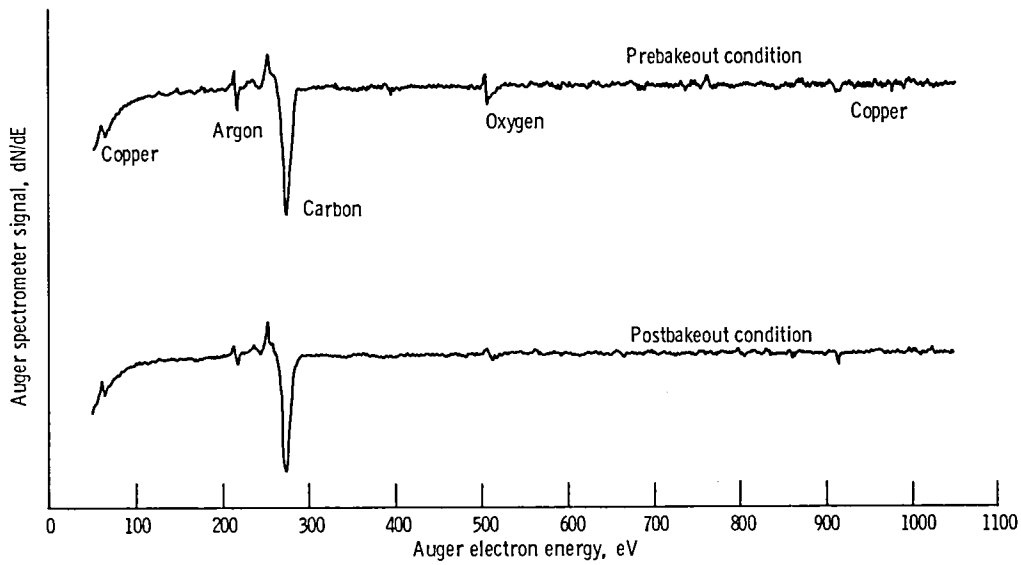
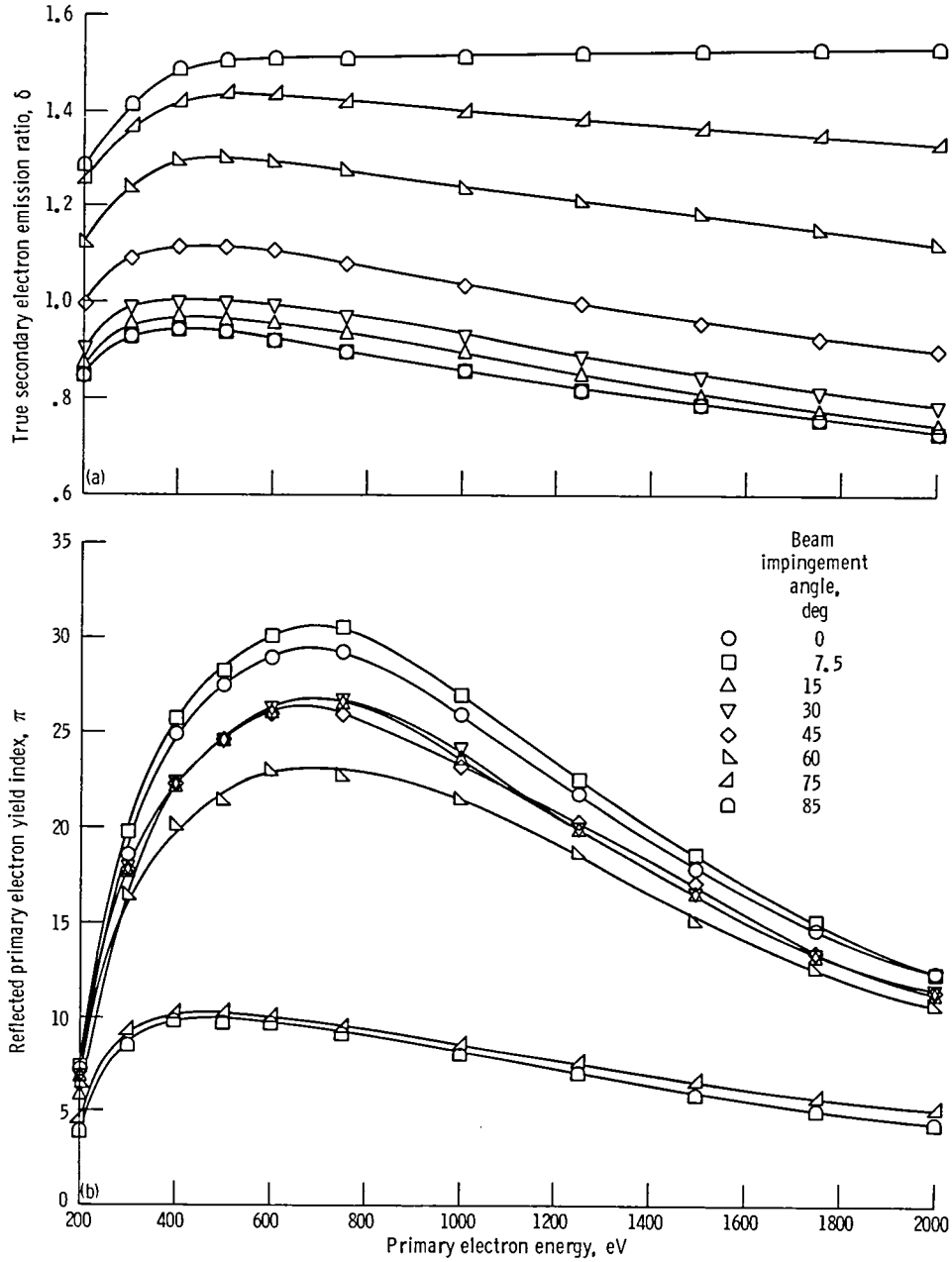


Figure 8.—Typical pre- and postbakeout Auger spectra for textured carbon on copper substrate.

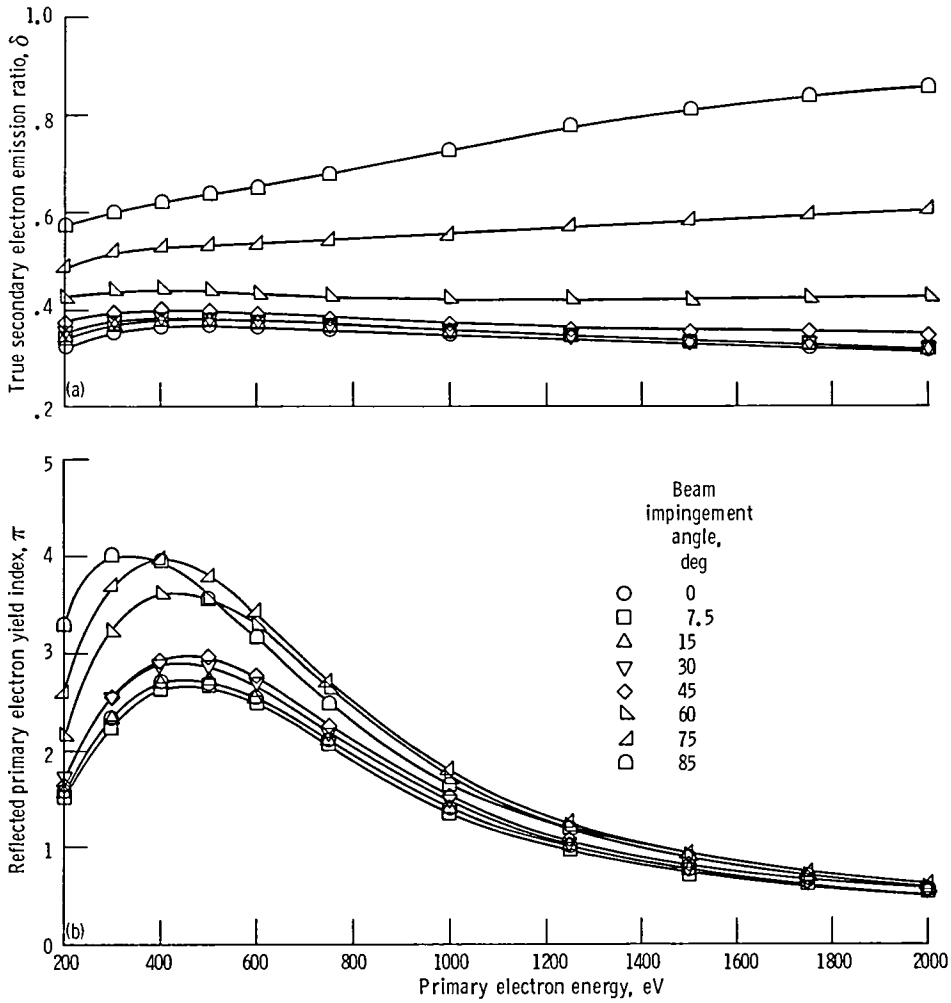


(a) True secondary electron emission ratio.
(b) Reflected primary electron yield index.

Figure 9.—Characteristics of untreated copper surface as function of primary electron energy.

The increase in true secondary electron emission ratio with electron beam impingement angle for the textured carbon on copper substrate samples is in agreement with the characteristics of the ion-textured pyrolytic graphite, high-purity isotropic graphite, and copper surfaces reported in references 6 and 7. Those surfaces were similar to the surfaces of the present study in that they also were also characterized by dense arrays of randomly positioned microscopic spires or peaks. With a direct (0°) electron beam impingement angle, many of the electrons strike the spire walls or the spire bases. Because many of the true secondary electrons that are generated then are repeatedly intercepted by the nearby spire walls, the net emission from the projected surface area is reduced. As the electron beam impingement angle is increased, beam penetration into the complex surface structure is reduced. The resulting lower secondary electron trapping effect permits the net true secondary electron emission to increase.

All three textured carbon surfaces on copper substrates exhibited true secondary electron emission ratios significantly lower than those of untreated copper (fig. 9(a)). Sample 2 (fig.



(a) True secondary electron emission ratio.
(b) Reflected primary electron yield index.

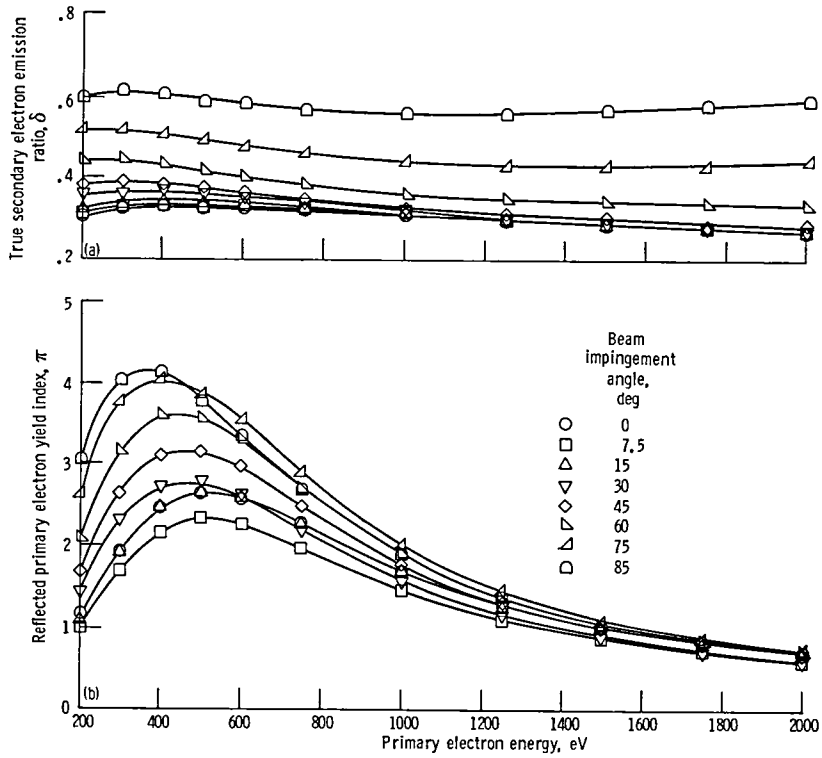
Figure 10.—Characteristics of textured carbon on copper substrate sample 1 as function of primary electron energy.

11(a)) displays modestly lower emission ratios than does sample 1 (fig. 10(a)), but sample 3 (fig. 12(a)) clearly exhibits the lowest ratio values at all beam impingement angles and primary electron-beam energies investigated. At least in the range covered in this study, the direct interrelationship among carbon surface texture feature development, true secondary electron emission suppression, and texturing period are apparent. The experimentally determined true secondary electron emission characteristics of the sample which was textured for 4 hr were quite similar to those of sample 3 and are not included in this report.

Reflected primary electron yield.—Curves presenting the reflected primary electron yield index π as a function of primary electron beam energy and beam impingement angle for the surfaces included in this study appear in figures 9(b), 10(b), 11(b), and 12(b).

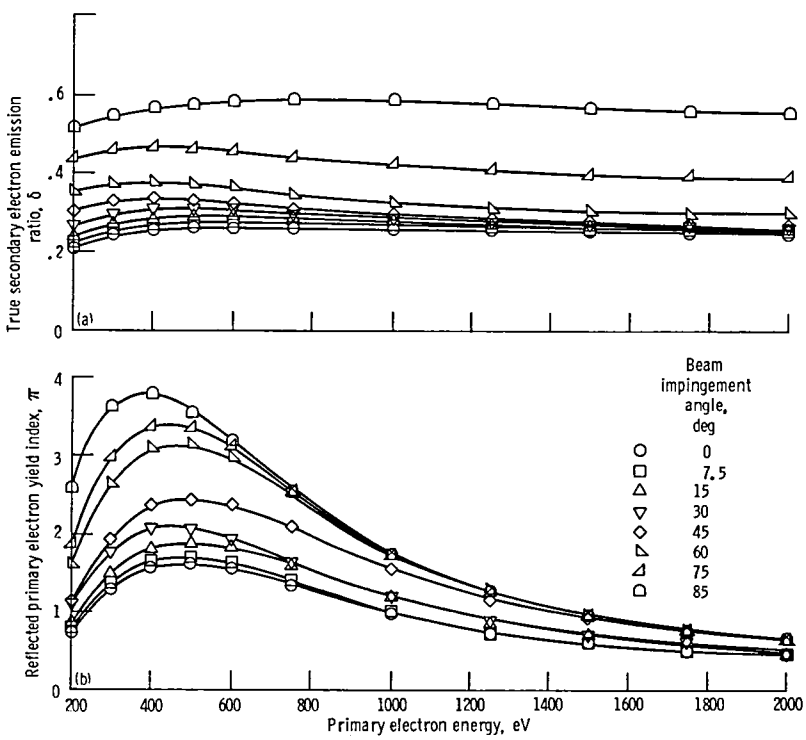
The relatively smooth untreated copper surface (fig. 9(b)) exhibits generally decreasing levels of reflected primary electron yield index with increasing beam impingement angle over the primary electron beam energy range investigated, as reported in reference 7. For this surface, impinging electrons that undergo elastic collisions reflect in directions away from the Auger CMA increasingly as the beam impingement angle is increased. This effect results in increasingly smaller measurements of reflected primary electron yield. The textured carbon surfaces on copper substrates (figs. 10(b), 11(b), and 12(b)), however, display generally increasing reflected primary electron yield index with increasing beam impingement angle over the same primary electron beam energy range. As the beam impingement angle is increased, much of the area on which the beam impinges (the sides of the spires) is rotated so that it faces more directly toward the Auger CMA. This results in an increase in measured reflected primary electron yield as the beam impingement angle is increased.

In parallel with the trends of the true secondary emission properties of the textured carbon surfaces on copper substrates, all the textured sample surfaces exhibited sharply lower



(a) True secondary electron emission ratio.
(b) Reflected primary electron yield index.

Figure 11.—Characteristics of textured carbon on copper substrate sample 2 as function of primary electron energy.



(a) True secondary electron emission ratio.
(b) Reflected primary electron yield index.

Figure 12.—Characteristics of textured carbon on copper substrate sample 3 as function of primary electron energy.

reflected primary electron yield indices than those of the untreated copper surface. The yield indices for sample 3 presented in figure 12(b) are lower at all primary electron energies and beam impingement angles investigated than those for sample 1 (fig. 10(b)) and 2 (fig. 11(b)). At primary electron energies of 200 to about 1400 eV and at beam impingement angles up to about 45°, the reflected primary electron yield indices for sample 2 are modestly lower than those for sample 1.

From the standpoint of achieving the lowest attainable primary electron yield index by using the procedures and texturing period range considered in this study to produce textured carbon surfaces on copper substrates, the development surface characteristics of sample 3 are preferred compared with those of the other two samples.

Conclusions

True secondary electron emission and relative reflected primary electron yield characteristics of three different novel textured carbon surfaces on copper substrates were experimentally determined and compared with those of an untreated copper surface. (All copper surfaces used in this study were oxygen-free, high-conductivity grade.) A specialized physical sputtering process developed at the NASA Lewis Research Center was used to produce the textured surfaces. The surfaces were tested over a range of primary electron beam energies from 200 to 2000 eV and at beam impingement angles from direct (0°) to near grazing (85°). The purpose of the investigation was to asses the use of the textured carbon surfaces on copper substrates for electrodes in multistage depressed collectors (MDC's) for high-efficiency microwave amplifier traveling-wave tubes (TWT's) for space communications and aircraft applications. To attain high efficiency in MDC's, the electrode surfaces must have low secondary electron emission characteristics. An untreated copper surface was used as a basis for comparison for the experimental surfaces examined because copper is currently in wide use as MDC electrode material.

While the three textured carbon surfaces on copper substrates were all produced with the same basic sputtering parameters and fixture arrangements, they were textured for different periods, 1 hr (sample 1), 2 hr (sample 2), and 3 hr (sample 3). Other samples textured for 1/2 hr were unusable because of incomplete substrate coverage and texture formation and were excluded from the study. Another sample textured in the same way for 4 hr had surface features and secondary electron emission characteristics quite similar to those of sample 3 and also was not included.

All three textured carbon surfaces on copper substrates exhibited sharply lower true secondary electron emission and relative reflected primary electron yield levels for the range of conditions examined than those of untreated copper. Sample 3 displayed the lowest secondary electron emission characteristics by a significant margin, while the emission characteristics of sample 2 were only modestly lower than those of sample 1. Therefore, from the standpoint of secondary electron emission characteristics for the samples in this study, textured carbon surfaces on copper substrates prepared in the manner described for sample 3 clearly have the greater potential to improve MDC and therefore TWT overall efficiency.

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio, September 15, 1985

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15. Supplementary Notes

16. Abstract

Experimentally determined values of true secondary electron emission and relative values of reflected primary electron yield for a range of primary electron beam energies and beam impingement angles are presented for a series of novel textured carbon surfaces on copper substrates. (All copper surfaces used in this study were oxygen-free, high-conductivity grade.) In addition, a detailed description of the method of preparation of the surfaces is included. The purpose of this investigation was to provide information necessary to develop high-efficiency multistage depressed collectors (MDC's) for microwave amplifier traveling-wave tubes (TWT's) for communications and aircraft applications. To attain the highest TWT signal quality and overall efficiency, the MDC electrode surface must have low secondary electron emission characteristics. While copper is the material most commonly used for MDC electrodes, it exhibits relatively high levels of secondary electron emission unless its surface is treated for emission control. The textured carbon surface on copper substrate described in this report is a particularly promising candidate for the MDC electrode application. Samples of textured carbon surfaces on copper substrates typical of three different levels of treatment were prepared and tested for this study. The materials were tested at primary electron beam energies of 200 to 2000 eV and at direct (0°) to near-grazing (85°) beam impingement angles. True secondary electron emission and relative reflected primary electron yield characteristics of the textured surfaces were compared with each other and with those of untreated copper. All the textured carbon surfaces on copper substrate tested exhibited sharply lower secondary electron emission characteristics than those of an untreated copper surface. Of the three textured surfaces tested, one clearly yielded the lowest emission characteristics.

17. Key Words (Suggested by Author(s)): Secondary electron emission; Graphite; Carbon; Copper; Traveling-wave tube; Multistage depressed collector

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